Pure Quantum Correlations Between Bright Optical Beams

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The pure quantum correlations totally independent of the classical coherence of light have been experimentally demonstrated. By measuring the visibility of the interference fringes and the correlation variances of amplitude and phase quadratures between a pair of bright twin optical beams with different frequencies produced from a non-degenerate optical parametric oscillator, we found that when classical interference became worse even vanished, the quadrature quantum correlations were not influenced, completely. The presented experiment obviously shows the quantum correlations of light do not necessarily imply the classical coherence.

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Both quantum and classical correlations of light fields are extensively applied in optical communication, information processing and optical measurements. The relationship between quantum and classical correlations is a widely attended issue, recently[1, 2, 3, 4, 5]. Although it has been theoretically proved that quantum correlations can exist without accompanying classical correlations[2, 5], there is no experiment specially to clarify this arguable problem so far. The entangled optical modes with quantum correlations of amplitude and phase quadratures have been successfully utilized in the quantum information with continuous variables (CV)[6] to realize the unconditional quantum teleportation, quantum dense coding, entanglement swapping and quantum key distribution[7, 8, 9, 10]. The two entangled optical modes used in all above-mentioned experiments are frequency-degenerate produced from optical parametric oscillators (OPO) operating below the oscillation threshold, thus they have also good classical coherence naturally. In CV quantum information systems the balanced-homodyne-detectors (BHD) are used for the correlation measurements and the signal extraction, usually. For directly applying the fundamental wave of the pump laser to be the local oscillator in BHD the entangled optical modes with a degenerate frequency are necessary, which easily make a false intuition to think that the classical coherence is contained in quantum correlations. The consideration seems reasonable from the general conception that classical physics is a special case of quantum physics, so we may think that after depleting the quantum correlations the classical correlations will be ultimately retained. It is a well-known fact that the quantum correlations are much more difficult to be generated and observed than classical coherence. For example, there is classical coherence between two optical beams split from a laser always, but there is no any quantum correlation in them. It is a generally recognized fact that quantum correlations may vanish when classical correlations exist. However, no more attentions have been paid to the opposite problem, especially there is no the experimental study to demonstrate the existence of quantum correlations without classical coherence although the theoretical discussion on this problem has been presented very recently[5].

For the "bright" light field the particle effects do not dominate, the quantum nature of which is mainly characterized by the presence of quantum noise. The coherent state is a minimum uncertainty state with equal noise fluctuations in the two quadrature components and is the closest quantum approximation to the light field generated by a laser. In an ideal light field of the coherent state all classical noises vanish and only the quantum noises limited by the minimum uncertainty of quantum mechanics are retained. The quantum noises of a coherent state are defined as the quantum noise limit (QNL).

According to quantum mechanics the quantum correlations existing between spatially separated optical beams can be stronger than that allowed by classical physics. With bright beams of light the quantum properties are encapsulated in the noise sidebands around its carrier frequency. For technical and engineering applications in CV quantum information systems, we are more interested in correlations between the amplitude and phase quadrature fluctuations of the spatially separated beams, recorded by separated detectors. The quadrature correlations of optical beams can be quantified by measuring the sum ($V\widehat{X}_+$, $V\widehat{Y}_+$) and the difference ($V\widehat{X}_-$, $V\widehat{Y}_-$) variances of the two quadratures:

$$V\widehat{X}_\pm = \frac{1}{2} < (\delta\widehat{X}_1 \pm \delta\widehat{X}_2)^2 >, \tag{1}$$

$$V\widehat{Y}_\pm = \frac{1}{2} < (\delta\widehat{Y}_1 \pm \delta\widehat{Y}_2)^2 >, \tag{2}$$

where $\delta\widehat{X}_{1(2)}$ and $\delta\widehat{Y}_{1(2)}$ are the fluctuations of amplitude ($\widehat{X}$) and phase ($\widehat{Y}$) quadratures for the optical beam 1 (2), respectively. If beam 1 and beam 2 are the coherent light with the noise at QNL, we have $V\widehat{X}_+^{coh} = V\widehat{X}_-^{coh} = V\widehat{Y}_+^{coh} = V\widehat{Y}_-^{coh} = 1$ which are taken as the normalized QNL for measuring the quantum correlations[6, 11], when $V\widehat{X}_+(V\widehat{Y}_+)$ is smaller than 1 the amplitude (phase) quadratures of the two beams are quantum anticorrelated and if $V\widehat{X}_-(V\widehat{Y}_-)$ falls below 1 they are quantum correlated. Such correlations can not be observed in classical light and can not be consistently accommodated in a classical theory, so we say that they derive from the quantum property of light field and essentially represent the pure quantum correlations apart from classical correlations.

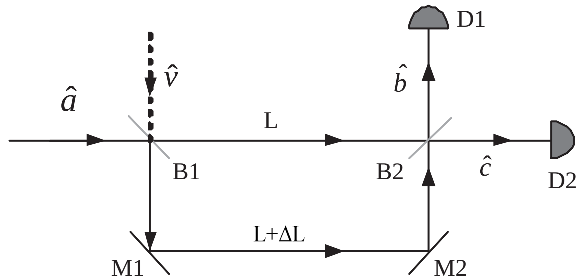

FIG. 1: The diagram of M-Z interferometer with an unbalanced arm length. $B_{1(2)}$, 50% beam-splitter; a, input optical mode; v, the input vacuum field, b and c, two output modes.

The CV entanglement of two bright optical beams is connected to the non-local correlations between quantum uncertainties of the conjugate variables, amplitude and phase quadratures. There have been a lot of theoretical publications to discuss the criteria of the optical entangled states with the CV correlations[12, 13, 14, 15, 16, 17, 18, 19, 20]. For the experiments where the observables are the amplitude and phase quadratures of optical fields, it is convenient to use the following the sufficient non-separability criterion for any two-mode bipartite state[15, 16]

$$V\widehat{X}_{\pm} + V\widehat{Y}_{\mp} < 2. \tag{3}$$

For a pair of optical beams with $V\widehat{X}_{+} < 1$ and $V\widehat{Y}_{-} < 1$ we say it is an entangled quantum state with quadrature-amplitude anticorrelation and quadrature -phase correlation. If $V\widehat{X}_{-} < 1$ and $V\widehat{Y}_{+} < 1$ we have an entangled state with quadrature-amplitude correlation and quadrature-phase anti-correlation. We are not able to obtain an entangled state with $V\widehat{X}_{+} < 1$ and $V\widehat{Y}_{+} < 1$ (or $V\widehat{X}_{-} < 1$ and $V\widehat{Y}_{-} < 1$) simultaneously since it violates the uncertainty principle of quantum mechanics[11, 12, 13].

On the other hand, the interference phenomenon between light waves directly characterizes the classical coherence of optical field, which can be quantified by the visibility (Vis) of the interference fringes. For the interference between two optical beams with different frequencies ν_1 and ν_2, we easily deduce

$$V_{is} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = Exp[-\frac{(\nu_1 - \nu_2)^2}{2\Delta\nu^2}], \tag{4}$$

where, I_{max} and I_{min} are the maximum and the minimum values of the interference intensities, respectively. In Eq.(4) we have assumed that the two optical beams are produced from a light source simultaneously and the delay time of the interference between them is taken as zero. The $\Delta\nu$ is the Gaussian frequency spread of each beam.

O. Glöckl et al. presented an elegant scheme which allow us to perform the sub-shot-noise measurements of the phase and amplitude quadratures of a bright optical beam as well as to determine the corresponding QNL experimentally without the need of a separate local oscillator by using a set of Mach-Zehnder interferometer with unbalanced arm lengths[21].The diagram of the interferometer is shown in Fig.1. $B_{1(2)}$ is a 50% beam-splitter and $M_{1(2)}$ is a mirror of 100% reflectivity. $\widehat{a}$ is the measured input optical mode, $\widehat{b}$ and $\widehat{c}$ are the two output modes. $\widehat{v}$ denotes the vacuum field with a vacuum noise $\delta\widehat{X}_0 = \delta\widehat{Y}_0 = 1$ and a zero average intensity. D_1 and D_2 are the photodiodes to detect the photocurrents. L and $L + \Delta L$ are the lengthes of the short and long arms of the interferometer, respectively. It has been demonstrated when the relative optical phase shift between two optical fields on B_2 equals to $\varphi = \pi/2 + 2k\pi$ (k an integer) and the phase shift of the spectral component of rf (radio frequency) fluctuations at a sideband mode (Ω) is controlled to $\theta = \pi$, the fluctuations of the sum and the difference photocurrents of $\widehat{b}$ and $\widehat{c}$ in the frequency space are proportional to the vacuum noise level [$\delta\widehat{X}_0(\Omega)$] and the spectral component of the phase quadrature of mode $\widehat{a}$ [$\delta\widehat{Y}_a(\Omega)$], respectively. That is, the evaluations of the sum [$\widehat{n}_b(\Omega) + \widehat{n}_c(\Omega)$] and the difference [$\widehat{n}_b(\Omega) - \widehat{n}_c(\Omega)$] of the spectral components at sideband frequency Ω are[21, 22]

$$\delta\widehat{n}_b(\Omega) + \delta\widehat{n}_c(\Omega) = a\delta\widehat{X}_0(\Omega), \tag{5}$$

$$\delta\widehat{n}_b(\Omega) - \delta\widehat{n}_c(\Omega) = a\delta\widehat{Y}_a(\Omega), \tag{6}$$

where $\widehat{n}_b = \widehat{b}^{+}\widehat{b}$ and $\widehat{n}_c = \widehat{c}^{+}\widehat{c}$ are the photon number operators of the output modes $\widehat{b}$ and $\widehat{c}$, a is the classical amplitude (a is assumed to be real) of the input mode $\widehat{a}$. $\delta\widehat{X}^{coh}(\Omega) = a\delta\widehat{X}_0(\Omega) = a$ is the normalized QNL of a coherent light with a classical amplitude a. In the experimental measurements the value of a always is taken as 1 for simplification and without losing the generality. Removing B_1 the mode $\widehat{a}$ directly arrives B_2 and the two detectors (D_1 and D_2) constitute a normal balanced detection system. In this case we have[21, 22]

$$\delta\widehat{n}_b(\Omega) + \delta\widehat{n}_c(\Omega) = a\delta\widehat{X}_a(\Omega), \tag{7}$$

$$\delta\widehat{n}_b(\Omega) - \delta\widehat{n}_c(\Omega) = a\delta\widehat{X}_0(\Omega). \tag{8}$$

It means that the sum (Eq.7) and the difference (Eq.8) photocurrents evaluate the fluctuation of the amplitude quadratures and the QNL of the input mode $\widehat{a}$, respectively. Therefore using the unbalanced M-Z interferometer we can conveniently measure the quantum fluctuations of the amplitude and the phase quadratures as well as scale the QNL of an optical beam.

The experimental setup is depicted in Fig.2. The bright optical twin beams with different frequencies are generated

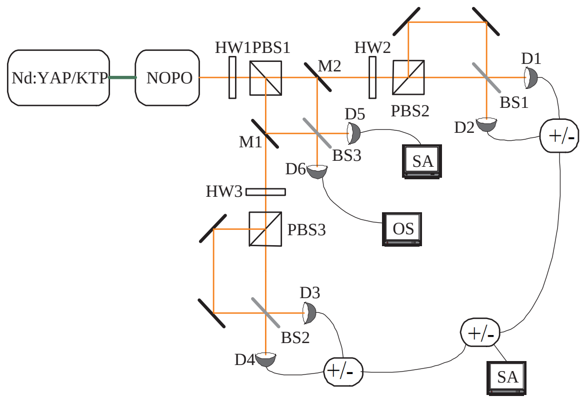

FIG. 2: (Color online) Schematic of experimental setup: Nd:YAP/KTP, laser source; HW1-3, $\lambda/2$ wave plate; PBS1-3, polarizing beam splitter; BS1-3, 50/50 beam splitter; M1-2, movable reflection mirror; D1-6, ETX500 InGaAs photodiode detectors; SA, spectrum analyser; OS, oscilloscope.

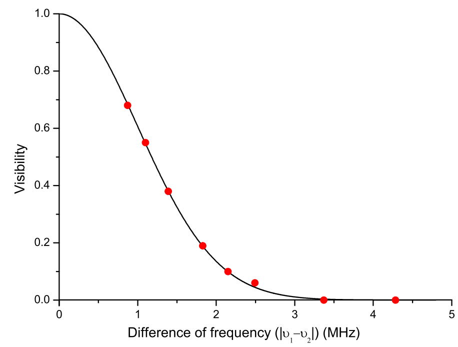

FIG. 3: (Color online) The dependence of the visibility of interference fringes on the difference of frequency ($|\nu_1 - \nu_2|$). Solid line is the calculated curve with Eq.4 ($\Delta\nu = 1.0MHz$); $\bullet$, the measured data.

from a nondegenerate OPO (NOPO) consisting of a type-II KTP ($KTiOPO_4$) crystal inside an optical resonator, which is pumped by an intracavity frequency-doubling Nd:YAP (Nd-dropped $YAlO_3$) laser. The second-harmonic wave at 540 nm from the laser serves as the pump field of the NOPO. Through a frequency down-conversion process inside the NOPO above the threshold a pair of bright optical twin beams with orthogonal polarizations is obtained in the output field, which just is the signal and idler modes in the KTP crystal[8, 12, 13]. The output twin beams are separated by a polarizing-beam-splitter (PBS1) and then they are detected by the two sets of unbalanced Mach-Zehnder (M-Z) interferometer, respectively. The polarizing-beam-splitter PBS2 and PBS3 serve as the input beam-splitters (corresponding to B1 in Fig.1) of the two interferometers, respectively. The three half-wave plates HW1, HW2 and HW3 are used for the polarization alignment of the input beams on the three PBSs respectively. By rotating the polarization orientation of HW2 and HW3 we can conveniently switch between amplitude and phase quadrature measurements. The beam-splitter BS1 (BS2) of 50% is the output coupler of the interferometer, the output beams of which are detected by the photodiodes D1 and D2 (D3 and D4). In the two arms of the interferometer the light beams transmit in the optical fibers with a refraction of 1.55. The length difference ΔL between the long and the short arm is 48m to satisfy the requirement of $\theta = \pi$ for the phase-quadrature measurement at the sideband frequency of $2MHz$[21]. The measured photocurrents by D1 and D2 (D3 and D4) are combined with the positive or negative power combiner (+/-) to give the QNL and the quadrature fluctuations according to Eqs.(5)-(8). When two movable mirrors M1 and M2 of 100% reflectivity are moved respectively in one of the twin beams, the reflected beams from each mirror are combined on a beam-splitter of 50% (BS3) for the measurement of classical coherence. The output photocurrents from the detector D5 is connected to a spectrum analyzer (SA) for measuring the frequency difference between twin beams ($|\nu_1 - \nu_2|$) by means of their beating signal. The output from D6 is sent to an oscilloscope (OS) for measuring the visibility of the interference fringes. Since the α-cut KTP crystal used in our system has a broad full temperature-width of about $40^O C$ around $63^O C$ for achieving the type-II noncritical phase matching, we can tune the frequencies of twin beams by changing the temperature of KTP which is placed in an electronic temperature-controlled oven.

Fig.3 shows the dependence of the visibility of the interference fringes on the frequency difference ($|\nu_1 - \nu_2|$). The frequency spread of each beam from the NOPO is $\Delta\nu \approx 1.0MHz$. The solid curve calculated with Eq.4 is in good agreement with the experimentally measured data ($\bullet$). When ($|\nu_1 - \nu_2|$) increases to $1.41MHz$ the visibility reduces to $1/e$ and when $|\nu_1 - \nu_2| > 3.37MHz$ the interference fringes totally vanish ($V_{is} \sim 0$). In this case, we say, there is no any classical coherence between the two optical beams.

Removing M1 and M2, we measured the quantum correlations of the twin beams. Subtracting (adding) the two photocurrents of the amplitude (phase) quadratures measured respectively by each M-Z interferometer according to Eq.7 (Eq.6) with a negative (positive) power combiner (+/-), we can obtain the correlation (anticorrelation) variances $V\widehat{X}_-$ ($V\widehat{Y}_+$) of the amplitude (phase) quadratures between the twin beams. The measured correlation variances are shown in Fig.4. Both measured $V\widehat{X}_-$ ($\bigstar$) and $V\widehat{Y}_+$ ($\blacktriangle$) are below the normalized QNL (0dB) and the correlations almost keep constant in the region of $-83.2GHz < (\nu_1 - \nu_2) < 860GHz$, where $V\widehat{X}_-$ and $V\widehat{Y}_+$ are $3.1 \pm 0.1dB$ and $1.5 \pm 0.1dB$ below the QNL, respectively, which are in reasonable agreement with the calculated results (solid line) according to the quantum correlation formula deduced for NOPO above the threshold by Fabre et al.[23], which are

$$V\widehat{X}_- = S_0[1 - \frac{\eta\zeta^2\xi}{1 + (\frac{f}{B})^2}], \quad (9)$$

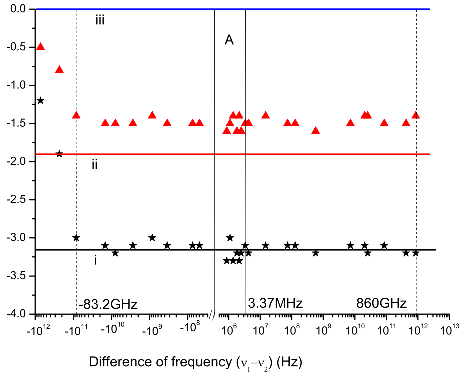

FIG. 4: (Color online) The measured noise power of the twin beams at 2 MHz dependent on the difference of frequency $(\nu_1 - \nu_2)$. i, the calculated of amplitude correlation variance; ii, the calculated of phase anticorrelation variance; iii, the QNL; ★, the measured amplitude correlation variances; ▲, the measured phase anticorrelation variances. In the region A of $(|\nu_1 - \nu_2|) < 3.37MHz$ both classical and quantum correlations exist. Outside the region A only quantum correltions exist without classical coherence.

$$V\widehat{Y}_{+} = S_0[1 - \frac{\eta\zeta^2\xi}{\sigma^2 + (\frac{f}{B})^2}], \qquad (10)$$

where, $f = \Omega/2\pi$ is the noise frequency, S_0 is the QNL, B and ξ are cavity bandwidth and the output coupling efficiency of NOPO, ζ is the transmission efficiency of M-Z interferometer, η is the detective efficiency, and σ $(= \sqrt{\frac{P}{P_0}})$ is the pump parameter (P is the pump power and P_0 is the threshold pump power of the NOPO). For our experimental system, the parameters are $\eta = 90\%$, $\zeta = 81\%$, $\xi = 88\%$, $\sigma = \sqrt{\frac{195mW}{130mW}} = 1.22$, $B = 15.4MHz$ and $f = 2MHz$. In the measurements of the correlation variances (Fig.4) we use the normalized QNL ($S_0 = 1$, line iii in Fig.4). The measured amplitude correlation variances (★) match perfectly with the calculated result from Eq.(9) (line i). However the measured phase correlation variances (▲) are higher by $0.3dB$ than the theoretical calculation because the worse mode-matching efficiency and the influences of the excess and spurious phase noises in the pump field have not been involved in the calculation with Eq.10 (line ii). The complicated factors influencing the phase correlation of twin beams have been analyzed detailedly in Refs.[24] and [25]. The measured value of $(V\widehat{X}_{-} + V\widehat{Y}_{+})$ is

$$V\widehat{X}_{-} + V\widehat{Y}_{+} = 1.20 < 2. \qquad (11)$$

The result demonstrates the quantum entanglement of the twin beams without the classical coherence.

For the conclusion, the presented experiment proves when the frequency difference $(|\nu_1 - \nu_2|)$ between twin beams is larger than $3.37MHz$, the interference fringes depending on the classical coherence totally vanish, but the quadrature quantum correlations are not influenced completely in the region of $860GHz$. In the experiment, the frequency changes of the twin beams were achieved by tuning the temperature of KTP crystal around the central temperature ($\sim 51^{O}C$) with a degenerate frequency of twin beams. When $(\nu_1 - \nu_2) < -83.2GHz$ or $(\nu_1 - \nu_2) > 975GHz$, the phase-matching condition for the nonlinear interaction is broken down because the temperature of the crystal has surpassed the phase-matching bandwidth. In this case the quantum correlation will decrease due to that the effective nonlinear coefficient of the KTP crystal is reduced[6, 12], thus the phenomenon of the correlation decrease over phase-matching temperature region does not connect with the classical coherence of light (Seeing the frequency region of $(\nu_1 - \nu_2) < -83.2GHz$ in Fig.4. The data in the region of $(\nu_1 - \nu_2) > 860GHz$ were not measured since the temperature of the KTP crystal is not able to be increased continuously due to the limitation of the oven.).

In the quantum optics, the QNL is a detectable boundary between the classical and the quantum effects. Using the boundary we verified that the existence of the quantum correlations may totally not depend on the classical coherence. The experiment provides us a convenient system and scheme to generate and study the pure quantum correlations with vanishing classical correlations. On the other hand, it makes us sure that the quantum correlations can exist in a pair of optical twin beams with very different frequencies, which is important for quantum communication since one of them may match with the atomic transition for information memory and other one may match the transmission in optic fiber.

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